

Student questions: James Lyons colloquium on “Comparing a star to its planets: A story of light stable isotopes in the solar system”

November 28, 2018

Question 1: What projects are in the works geared towards obtaining isotopic compositions of exoplanets? Ground based observations using large telescopes with high-resolution IR spectrometers (called high-dispersion spectroscopy). This should work for ^{13}CO in hot Jupiters. There is some chance of seeing CH_3D with JWST at 4.6 microns, but we probably first need to find CH_4 in an exoplanet atmosphere – it has been missing thus far.

Question 2: What is the furthest location in our solar system (or the Universe) where we've been able to confidently measure isotopic composition? Isotopic measurements have been made in CO in galaxies with moderately high redshifts. They have extreme isotope ratios but large uncertainties (not surprisingly). We have a good N isotope ratio for Jupiter from the Galileo probe – that might be the best most-distant isotope ratio measured in the solar system. There are also some good quality D/H measurements for a few comets. There are an enormous number of isotope ratio measurements in molecular clouds, and less in protoplanetary disks. Isotopes play a huge role in astrochemistry.

Question 1: Would the isotopic distribution mechanisms depend on the type of star in the system? This is certainly a possibility and is a big part of why we try to understand in detail the processes that were at work in our solar system. The formation environment is also likely to play a large role, e.g. did the stellar (or solar) system form in a large cluster of other young stars, or in a more quiescent environment? A large cluster of stars increases the likelihood of nearby massive stars, which can supply a large flux of FUV radiation and supernova products.

Question 2: How could this process be applied to understanding formation and ultimately habitability of exoplanets in systems unlike our own? As an example, if photochemistry turns out to play the major role that is implied by a self-shielding explanation for C, N, and O isotopes in our solar system, then we can expect that photochemistry also reworked organic compounds in the solar nebula. This photochemical reworking may be crucial to the inventory of organic materials transported to early Earth. Exoplanet systems in which disk photochemistry is less important may lack some key organic compound reservoirs.

Question 1: Why can't we/aren't we already using Zinc Selenide crystals to look into exoplanet molecule cross-sections? For technical reasons. It's much easier to put quartz windows on a quartz tube and heat it up – there is no differential thermal expansion. There are no ZnSe tubes, so we have to combine ZnSe windows with a tube of some other composition (e.g., quartz or stainless steel), and provide a O-ring to take up the difference in thermal expansion of the tube and window materials. This can be done, although it limits us to temperatures up to about 700 K.

Question 2: How large was our Solar system's parent cloud compared to the current solar system size/our protoplanetary disk? We don't know the size of the entire cloud (we can take a guess from the number of stars it may have given birth to), but our solar system would have been formed from a small part of the cloud, a so-called cloud core. This was probably ~ 1 parsec in size.

Question 1: Do the other terrestrial planets also show an enrichment in ^{33}S as they do not have oxygen rich atmospheres? No sulfur species have been observed in the atmosphere of Mars. The regolith is sulfur-rich, and S isotope measurements on sulfur minerals in martian meteorites indicate some small amount of ^{33}S enrichment, possibly due to photolysis of SO_2 in an ancient volcanic plume. Venus has a massive amount of SO_2 and other sulfur species in the atmosphere. We don't have measurements of S isotopes for the Venus atmosphere, but there is a lot of interest in obtaining such data. It will most likely require a descent probe or balloon with a good mass spec for in situ measurements, or a sample return of some Venus atmosphere.

Question 2: Why is the standard for carbon based upon a phragmacone? Are all PDBs the same in carbon content, or is it just one specific PDB? A belemnite is used because it is a biogenic carbonate. The majority of surficial C on Earth is stored in biogenic carbonates, so the belemnite should be representative of that large C pool. The Pee Dee belemnites are probably quite uniform in isotope ratio, which may be why they were chosen. I'm sure an average of several was used.

Question 1: How does measuring the photosphere give measurements of isotope content in the solar wind? To get a solar wind isotope ratio from a photosphere isotope ratio (or vice versa) we have to account for isotope fractionation during the acceleration phase of the solar chromosphere and corona gas to form the solar wind. During that acceleration phase it is believed that protons collide with heavier nuclei (e.g., O, C, N and their isotopes) to impart enough momentum for the heavier ions to also escape the Sun. This process is known as inefficient Coulomb drag, 'inefficient' because the lighter protons are inefficient at transferring momentum to the heavier nuclei. This collisional process results in a mass-dependent fractionation such that the lighter isotopes are favored over the heavier isotopes. For example, the Genesis solar wind measurement was $\delta^{17}\text{O} = -80$ permil, $\delta^{18}\text{O} = -100$ permil, but the photosphere is about $\delta^{17}\text{O} = -60$ permil and $\delta^{18}\text{O} = -60$ permil (all relative to SMOW).

Question 2: What actually is self-shielding? Yes, I didn't spend enough time explaining this important concept. Consider a broadband UV light source (like most stars, but especially like an OB star). The CO molecule is dissociated from about 91-110 nm (in a H-rich environment). The absorption spectrum of CO at these wavelengths is composed of many hundreds of narrow lines. An isotope substitution (e.g., ^{13}C or ^{17}O) causes a small shift in the positions of the lines, such that the lines for $^{12}\text{C}^{16}\text{O}$ (the main isotopologue) and the minor isotopologues ($^{13}\text{C}^{16}\text{O}$, $^{12}\text{C}^{17}\text{O}$, $^{12}\text{C}^{18}\text{O}$) do not overlap. And keep in mind the approximate abundances: $^{12}\text{C}^{16}\text{O}/^{13}\text{C}^{16}\text{O} \sim 90$, $^{12}\text{C}^{16}\text{O}/^{12}\text{C}^{17}\text{O} \sim 2600$, $^{12}\text{C}^{16}\text{O}/^{12}\text{C}^{18}\text{O} \sim 500$. The much greater abundance of $^{12}\text{C}^{16}\text{O}$ means that if the column of CO gas is thick enough it will become saturated at the specific wavelengths that it dissociates (i.e., its specific line positions) long before any of the minor isotopologues. Once saturated photolysis of $^{12}\text{C}^{16}\text{O}$ stops, but because the other isotopologues are not saturated and have lines at slightly different positions, they continue to be dissociated. This produces an enormous enrichment of the minor isotopes (^{13}C , ^{17}O , ^{18}O). The enrichment of ^{17}O and ^{18}O is nearly equal so we get close to a slope 1 line in the O atoms produced during CO photolysis when $^{12}\text{C}^{16}\text{O}$ is shielding itself.

Question 1: Do we know whether there was vertical mixing in the solar nebula? **We don't know. Observations of other protoplanetary disks are still not yielding definitive answers on this issue. The difficulty is that the velocities are fairly small even in a turbulently mixed disk.**

Question 2: Will the Parker Solar Probe give any new data that may help your investigation of the isotope composition of the Sun? **Yes, almost everything that the Parker probe measures will be helpful. Parker will image the corona, measure E and B fields, and measure electrons, protons and ions. Of the isotopes, it will only measure ^3He and ^4He . It will measure ions such as C, O, N, Mg and Si, but not their isotopes. But all of these measurements will contribute to improving our understanding of how the corona works and how the solar wind is accelerated. Both of these issues are critical to understanding isotope fractionation in the formation of the solar wind.**

Question 1: What type of instrument would be better for the studies you're focusing on – mass-spec on the ISS or a satellite similar to Genesis to gather direct particles? **Rather than a mass spec, I would like a Fourier transform spectrometer that operates in the IR (aka FTIR) on the ISS. We're still haven't analyzed all of the Genesis data, so we don't need another one yet.**

Question 2: Could measuring other stable isotopes help to understand the 17/18O ratio?

Indirectly, yes. The C and N isotope ratios are telling us that planetary materials are enriched in the minor isotopes, as is the case for O isotopes. So we are exploring processes such as self-shielding or nuclear chemistry that can influence all of these isotopes.

Question 1: Why is it that we don't have isotope values for Jupiter? **We have N isotopes from the Galileo probe. We have C isotopes also but they have large error bars and are not very useful. The real problem is that we don't have O isotopes. The Galileo probe detected much less H_2O than expected, so we don't have $\delta^{18}\text{O}$ for Jupiter water. This is truly unfortunate.**

Question 2: What do you think are the reasonable implications for small organic molecules and the origin of life if the self shielding theory is true? **To answer this we would have to assess which organic molecules are produced photochemically in the solar nebula, by both gas phase and ice phase chemistry. Then we would have to assess the survival of this material during formation of Earth (probably little survives) and by deposition onto the proto Earth (more would survive). We would also need to reconcile photochemically produced organics with the well studied record of organics in carbonaceous chondrite meteorites. The meteorite record might already tell us something about the importance of photochemistry. Parent body processing has to be backed out to make that analysis useful.**

Question 1: Do you expect to find the same enrichments in gas giant's planets atmospheres? **We expect that Jupiter and the Sun should be isotopically similar. This is verified to be true for N isotopes. Uranus and Neptune are ice giants, so their isotope ratios will reflect primarily the ice-rich material that they accreted. I would be surprised if this material is isotopically the same as Jupiter.**

Question 2: Do you know of any missions that are starting up to studying the upper Earth atmosphere like we are doing on Mars? **Not that I'm aware of. A cubesat mission would certainly be appropriate. If anyone's interested in a cubesat with a small mass spec on board to measure upper atmosphere isotopes, let me know.**

Question 1: Why is the Sun not a good indicator of the bulk composition of the solar system?

The Sun *is* a good indicator of the bulk composition of the solar system, with the exception of D, Li, and Be.

Question 2: Do you look at isotope data from pre-solar grains? Only from the literature, but I do not do any presolar grain measurements. Maitrayee Bose in SESE works on presolar grains.

They are clearly important messengers of late-stage stars, and they provide isotopic and elemental samples of various types and stages of nuclear chemistry from late stage stars.

Question 1: Is it possible to have a mission like MAVEN orbiting Earth and measuring our Earth's upper atmosphere? It is certainly possible, but we haven't had one. Long ago they used to fire rockets into the upper atmosphere up to ~ 100 km, but not up to the escape altitude (~500 km). Again, it would be worth considering a cubesat.

Question 2: Why is the X-ray activity of the sun so important? The x-ray active Sun is in the upper chromosphere and corona. Much of our ignorance of the Sun occurs in this region of its atmosphere (e.g., the hot corona, the acceleration mechanism for the solar wind). That's why the Parker probe was sent.

Question 1: Is it possible that the Sun's bulk chemistry is not representative of the bulk material from which the solar system was formed? The Sun today is about 99.8 % of the mass of the solar system. The protoSun was about 98% or so of the mass of the protosolar system, including the solar nebula. Might the bulk Sun not be representative of the bulk material that formed the solar system? I would say, not likely. Might the bulk Sun differ from the bulk material that formed the planets, i.e., the solar nebula? This is more plausible. A well-timed injection of supernova material into the solar nebula could have influenced the composition of the planets disproportionately compared to the protosun due to the much greater area of the solar nebula. I'm sure constraints have already been placed on this possibility.

Question 2: Which of the three processes do you think to be the least likely? At the moment I would say that the non-statistical chemical reaction option is least likely to explain the difference in C, N and O isotopes between the Sun and terrestrial planets.

Question 1: Is the sulfur and its isotopes in the atmosphere increasing due to pollution or is it a phenomenon that has not been studied before and just beginning to be noticed? The sulfur mass-independent fractionation signature that I mentioned occurs in ancient sedimentary rocks > 2.4 Gyr old. In fact we do see much smaller, but non-negligible, sulfur MIF signatures in modern organo-sulfur pollutants in the troposphere. Ask me if you would like to know more.

Question 2: What makes certain samples and molecules have independent fractionation and others not behave that way? The fractionation mechanism that operates on these molecules is what determines whether they undergo MDF or MIF. Most molecules in Earth's atmosphere undergo MDF. But a few can be affected by MIF, due primarily to non-statistical chemistry (symmetry dependent) or due to self-shielding effects.

Question 1: What do we stand to learn from the isotopes of exoplanets if we have so little context? That is precisely what we are trying to address is the context for isotope differences in our own solar system. The exoplanets will come later. We still do not have even one isotopic ratio measurement of any element for any exoplanet. So we still have a ways to go. But in research one must look toward the clear and inevitable future.

Question 2: When can we expect to have isotopic data from the outer solar system? We have N isotope data. We do not have good C or O isotope data for Jupiter (the most important member of the outer solar system). I don't know when we can expect better data for Jupiter. In situ measurements are most likely needed. That means atmospheric probes.

Question 1: Are there additional objects, either with different delta-C's or different heliocentric orbits that have not been studied yet, that you would like to analyze? Yes, mostly Jupiter, but Uranus and/or Neptune would also be informative. Pretty much anything in the outer solar system, Pluto included.

Question 2: If the CO-shielding idea is under question (as you mentioned in your talk), what are some other possible alternatives that you find potential in? I find the possibility that injection of material from nearby late-stage stars could have been important to be interesting. It's not easy to see how this process could explain O isotopes in meteorites, apart from pure coincidence, but the idea is intriguing.

Question 1: How do you think the solar wind samples would have changed if they were collected from a different star-planet system and not the Solar System? Yes, almost certainly. How different I do not know.

Question 2: What accuracy were you able to achieve for the carbon monoxide measurements from the samples? This is an important question. Our solar CO measurements have 1-sigma uncertainties of ~ 1% of the mean for both $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ (^{17}O uncertainties were higher). For spectroscopic observations this is quite good. Mass specs with laboratory samples can do much better, but we don't have that option for the solar photosphere. Yes, we have the solar wind, but that's not the photosphere.

Question 1: You mentioned absorption overlaps between species you study and species of interest to others. What analysis techniques (or even data pipeline processes) tend to make the task of picking out features easier or harder? I'm not quite sure what the overlap question is referring to. For the Sun the analysis techniques are not pipelined – we actually need to look at lines on an individual basis. Most spectroscopy, including the exoplanet-related lab work, requires attention to small details in the spectra. A pipeline analysis of data is not really possible in these cases, and is not really necessary since we're not dealing with massive amounts of data. We use non-linear least squares fitting techniques to analyze the exoplanet lab spectra.

Question 2: Could any sulfur MIF-related speciation data be obtained from emission or reflectance spectra? (e.g. in the case of possibly sulfur-rich haze causing a flat transmission spectrum) In principle, yes, but in practice, not likely. To address sulfur MIF we would need an accurate measure of ^{33}S , a difficult task by remote spectroscopy. The text case is Venus. We need to show that we can extract this information for the Venus upper atmosphere (above cloud tops). We're not even close to doing this yet.

Question 1: What are the chances of terrestrial planets to have heavier elements like Lead, Bismuth in their atmosphere? The surface temperature of Venus is high enough to melt Pb (m.p. 327 °C). If there is any Pb on the surface of Venus, it will have a non-negligible vapor pressure. Bismuth, with a lower m. p., could have an even higher vapor pressure. Of course, these elements are not that abundant, so we do not expect a substantial abundance of either of them at the surface. But they could be present in a high-temperature atmosphere, Venus or warm/hot exoplanet.

Question 2: Are there ways that planetary atmospheres synthesize elements which are not present in their respective stars? Galactic cosmic rays induce nuclear reactions in atmospheres, and can produce isotopic species that are not yet produced in the parent star. For example the sun is busy converting H into He, but is not yet capable of any CNO cycle nuclear chemistry. However, GCRs can convert ^{14}N into ^{14}C via the reaction $n + ^{14}\text{N} \rightarrow p + ^{14}\text{C}$, in addition to a great many other minor reactions.

Question 1: How do you justify assuming homogeneity of the protoplanetary disc material? I assume homogeneity only in the initial composition of the solar nebula. It is quite clear that the solar nebula was not a uniformly homogeneous structure for its entire history.

Question 2: Could heavier isotopes like Si and Mg behave similarly to C, N, O? This is an important question. If nuclear chemistry is the primary mechanism responsible for the isotopic differences we see in C, N and O isotopes, then isotopic differences between the Sun and terrestrial planets may also be present in Si and Mg isotopes. We don't know yet. That is an active area of research.

Question 1: How will knowledge of the isotopic composition of our solar system's outer planets impact your theory? We know N isotopes for Jupiter, but we have lousy numbers for C and nothing for O. If Jupiter does not look like the Sun in C and O isotopes (it does in N isotopes), then the impact on the theory would be significant. We would have to reconsider the isotopic history of the solar system.

Question 2: Is it correct to assume that the isotopic composition of a star and its planets would be different in part because of the difference in temperatures and pressures? It's important to specify which temperature and pressure are being discussed. Are we talking about P and T of the solar nebula, the parent star, or the planet/exoplanet, or all of them. Or are we talking about the difference in the UV radiation field in these 3 environments?

Question 1: What will the comparison of isotopes chemistry in the upper atmospheres of Earth and Mars help us understand to the first order? It will tell us how these two atmospheres differ in isotopic composition in the gases that are lost to space. Because Mars has a low gravity (about 1/3 of Earth) and no magnetic field, atmospheric escape is more important for Mars than for Earth. We want to see the isotopic evidence for these differences in the two atmospheres.

Question 2: What causes self-shielding in CO? I describe this in detail in one of the answers above.

Question 1: How did you get interested in studying isotopic composition of the solar system? It is important in science to identify areas that are less well traveled. Isotopes in the solar nebula (and CO self-shielding more specifically) and S isotopes in early Earth's atmosphere were two less traveled areas. I chose to focus on them.

Question 2: What are the major methods that you use in your study to measure isotopic composition in extraterrestrial planets? Infrared spectroscopy. There are no reported isotopic ratios of anything or any exoplanet atmosphere up to the present. We expect this to change in the near future.

Question 1: What happened to the Sun's deuterium? The protoSun reached temperatures that burned D in the proton-proton chain reaction. D was long ago removed from the Sun by these reactions.

Question 2: How abundant is the Pee Dee Belemnite? It's in one location on N. & S. Carolina. I don't think it's all that abundant now, but that doesn't matter. We have the absolute ratio of C isotopes in PDB. When making mass spec measurements we measure relative to some other known standard, and then report the ratio relative to PDB. We don't need to have a sample of PDB in hand to report the ratio.

Question 1: What type of instrument would be required to measure isotopes of exoplanets? High-resolution IR spectrometers on large telescopes should work for some isotopes. This capability already exists, and is applicable to ^{12}CO (already detected) and should work for ^{13}CO (not yet detected).

Question 2: When normalizing the nitrogen isotope, is there a standard time, location, and elevation to sample the atmosphere? For the N isotope standard we use N_2 in the troposphere. The isotopic composition is quite uniform in N_2 until you get quite high in the atmosphere.

Question 1: What sorts of "anomalies" can be imprinted on the icy cores of collapsed ice clouds (from the slide with the diagram about cloud collapse)? If the cloud is exposed to FUV radiation from a large nearby star, then self-shielding anomalies (in CO and N_2) could be imposed on the gases in the cloud. Injections of gas and grains from late-stage stars could also impart anomalies. So the answer is that any anomaly that can be in the protoplanetary disk can also be in the molecular cloud core, although with different quantitative values.

Question 2: Could a combination of climate change and pollution effects alter SMOW enough that oxygen isotope calculations will need to be based around a new standard? The SMOW standard is stored in Vienna, and so cannot be affected by changes in ocean isotopic composition on Earth. But realistically it would be difficult to change O isotope ratios by just pollution. Climate change could alter the O isotope composition of the oceans by melting a large fraction of the ice caps.

Question 1: What do you think the time line is for measuring isotopic signatures of exoplanets, and how close does/will JWST get us? For C isotopes this could happen soon. The key is a good spectrometer on a large ground-based telescope. CRIRES on three VLT is the obvious candidate, and it should be running again soon. JWST could get us a detection of CH₃D at 4.6 microns, along with a CH₄ detection at (probably) 3.3 microns.

Question 2: Can you please explain vertical mixing again and why, since it is so important to account in these isotopic measurements, has it been excluded in previous studies? If CO self-shielding is to explain the O isotope distribution in the solar system, then the solar nebula gas must be fairly well mixed. The UV radiation that dissociates CO is confined to the upper 'UV-active' region of the solar nebula. If the nebular material is not vertically mixed, then most of the nebular CO will not be photodissociated, and therefore cannot undergo self-shielding. The question of vertical mixing is a crucial one, and is still debated for other protoplanetary disks.

Question 1: What is the reason for the "strange" point in the Oxygen isotope plot? There appears to have been a reservoir of nebular gas that was even more depleted in ¹⁷O and ¹⁸O than the Sun. It's not clear where this reservoir came from.

Question 2: What is the method scientists get the Sulfur isotope for the ancient atmosphere? By measuring the S isotope composition of sedimentary S-containing rocks, such as pyrites and barites. We are quite sure that the sulfur MIF signature was produced in atmospheric reactions, and that it then gets stored in sulfur species in the ocean, and eventually ends up in marine sediments.
